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Biomechanical comparison of three internal fixation configurations for low transcondylar fractures of the distal humerus

Yejun Zha[a,#], Kehan Hua[a,#], Yong Huan[b], Chen Chen[a], Weitong Sun[a], Shangwei Ji[a], Dan Xiao[a], Maoqi Gong[a], Xieyuan Jiang[a,*]

[a] *Department of Orthopedic Trauma, Beijing Jishuitan Hospital, No.31 Xinjiekou East Street, Xicheng District, Beijing 100035, China*
[b] *State Key Laboratory of Nonlinear Mechanics (LNM), Institute of Mechanics, Chinese Academy of Sciences, Beijing, China*

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ABSTRACT

Background: We aimed to evaluate the biomechanical stiffness and strength of different internal fixation configurations and find suitable treatment strategies for low transcondylar fractures of the distal humerus.

Methods and materials: Thirty 4th generation composite humeri were used to create low transcondylar fracture models that were fixed by orthogonal and parallel double plates as well as posterolateral plate and medial screw (PPMS) configurations (n=10 in each group) using an anatomical locking compression plate-screw system and fully threaded medial cortical screws. Posterior bending (maximum 50 N), axial loading (maximum 200 N) and internal rotation (maximum 10 N·m) were tested, in that order, for each specimen. Stiffness under different biomechanical settings among different configurations were compared. Another 18 sets of fracture models were created using these three configurations (n=6 in each group) and the load to failure under axial loading among different configurations was compared.

Results: Under posterior bending, the stiffness of parallel group was higher than orthogonal group ($P<0.001$), and orthogonal group was higher than PPMS group ($P<0.001$). Under axial loading, the stiffness of parallel group was higher than orthogonal group ($P=0.001$) and PPMS group ($P<0.001$); however, the difference between orthogonal and PPMS group was not statistically significant ($P>0.05$). Under internal rotation, the stiffness of parallel group was higher than orthogonal group ($P=0.044$), and orthogonal group was higher than PPMS group ($P=0.029$). In failure test under axial loading, the load to failure in the orthogonal group was lower than parallel group ($P=0.009$) and PPMS group ($P=0.021$), but the difference between parallel group and PPMS group was not statistically significant ($P>0.05$). All specimens in orthogonal group demonstrated "distal medial failure"; most specimens had "distal medial and trochlear failure" in the parallel group; most specimens exhibited "contact failure" in the PPMS group.

Conclusion: For treating low transcondylar fractures, the overall stiffness and strength of the parallel configuration were superior to those of the orthogonal and PPMS configurations. Nevertheless, the PPMS configuration can provide adequate stability and stiffness comparable to double-plate configurations under axial loading. Therefore, the PPMS construct may have certain clinical value.

Background

Distal humerus fractures are relatively rare in adults, with an incidence of 5.7 per 100,000 persons per year, accounting for approximately 2% of all fractures [1,2]. Low transcondylar fractures, as a special subtype, are even more uncommon, representing approximately 9% of all distal humerus fractures [3,4]. These particular injuries are characterized as simple transverse fracture lines that extend from the lateral epicondyle through the olecranon and coronoid fossa and to or just above the level of the medial epicondyle. Pertinently, these injuries are classified as extra-articular intracapsular fractures [5]. While open reduction and internal fixation (ORIF) is the preferred treatment, implant failure and nonunion are the main concerns. It may be difficult to maintain the stability of the distal fragment with ORIF due to the small fragment size, which makes it less likely that screws with sufficient number and length to provide adequate support can be placed, especially in the presence of poor bone quality [6–8]. Therefore, the stiffness and strength of internal fixations are determinant factors in choosing different configurations [5].

* Corresponding author.
E-mail address: jxy0845@sina.com (X. Jiang).
# (Yejun Zha and Kehan Hua contributed equally to this manuscript)

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Fig. 1. Low transcondylar fracture models (incomplete osteotomy). (a) Dorsal side. (b) Ventral side.

Parallel and orthogonal double-plate configurations are most commonly and widely applied in clinical practice for the treatment of distal humerus fractures [1,2,9-13]. Many previous studies have compared the biomechanical properties between these two configurations under different loading methods; however, these experiments were often carried out using either intercondylar fracture models or supracondylar fracture models with a relatively high osteotomy plane. Therefore, these models did not meet the definition of low transcondylar fractures [14–17]. In addition, for low transcondylar fractures, which have relatively simple morphological features but high risk of nonunion or delayed union, and double-plate configuration may cause more irritation problem in patients with thin soft tissue coverage especially in the medial side, it is particularly important to seek more minimally invasive fixation methods with sufficient stability, such as the posterolateral plate and medial screw (PPMS) configuration. Shimamura et al. [18] evaluated its biomechanical properties but reported very poor stability and strength in treating low transcondylar fractures, which was very likely due to the use of conventional reconstruction plates and semithreaded cannulated cancellous screws in their study.

Therefore, this study was designed to evaluate and compare the biomechanical properties between parallel and orthogonal double-plate configurations as well as of PPMS configurations using anatomical locking compression plate-screw system and fully threaded medial cortical screws for the stabilization of low transcondylar fractures of the distal humerus.

Materials and method

Fracture model

We used 4th generation composite humeri (Large, Left, item #3404, Sawbones; Pacific Research Laboratories Inc, Vashon, WA, USA), which is widely accepted as an adequate substitute material to simulate human bone, for mechanical testing [19,20]. To simulate low transcondylar fractures, a 5 mm wide incomplete osteotomy gap was created using a reciprocating saw in a transverse plane vertical to the axis of humeral shaft, with the lower margin of the gap starting at the widest distance between the lateral and medial epicondyles without comprising the articular surface (Fig. 1). The osteotomy gap, which was located at the lower middle part of the olecranon fossa, was designed to simulate metaphyseal comminution and most importantly to facilitate measurements of distal fragment displacement during biomechanical testing. The fragment within the gap was removed using an oscillating saw after internal fixation to ensure the accuracy and uniformity of the gap created in each fracture model.

Implant systems and configurations

The prepared fracture models were then fixed by an anatomical precontoured locking compression plate-screw system and fully threaded cortical screws (Synthes GmbH, Switzerland). Importantly, there were three methods of osteosynthesis in our experiment (Fig. 2): (A) orthogonal configuration (posterolateral and medial plates), (B) parallel configuration (lateral and medial plates), and (C) PPMS configuration (posterolateral plate and medial screw). The posterolateral and medial locking compression plates (LCPs) were anatomically mounted and fixed onto the radial column and ulnar column respectively, with three 3.5 mm locking screws inserted into the proximal fragment and three 2.7 mm screws into the distal part through the plates. The lateral LCPs were fixed with two 3.5 mm and one 2.7 mm locking screws inserted into the proximal fragment, and only two 2.7 mm polyaxial locking screws were inserted into the distal part due to its small volume. All the screws in the proximal fragment were bicortially inserted but the distal screws were carefully placed monocortically with the screws as long as possible without penetrating the opposite cortex or joint surface. The coronoid and olecranon fossa was

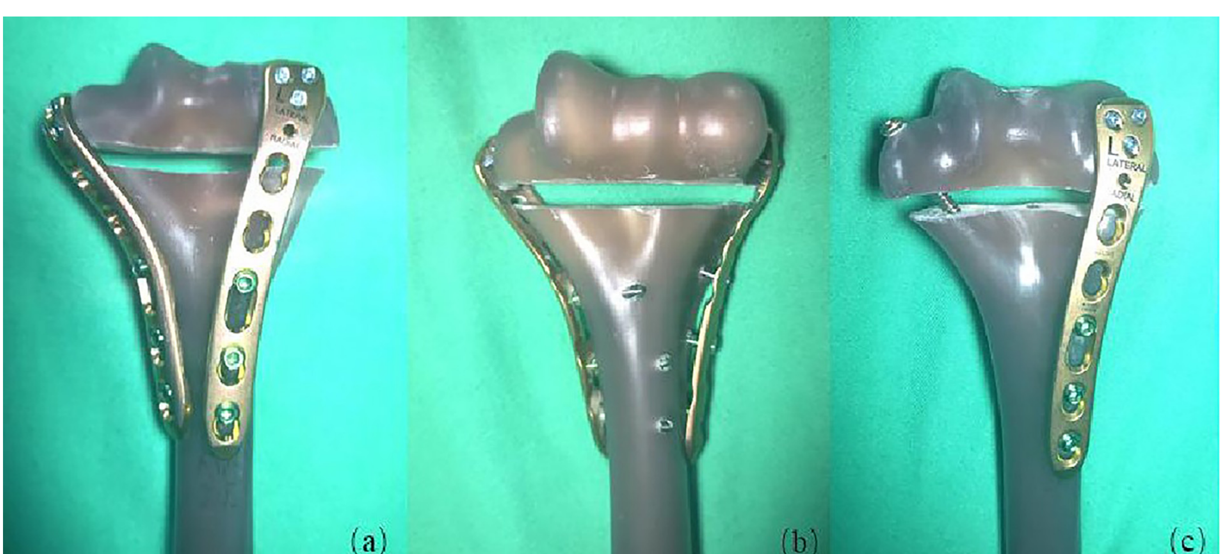

Fig. 2. Typical examples of three internal fixation configurations. (a) Orthogonal double-plate. (b) Parallel double-plate. (c) Posterolateral plate + medial screw (PPMS) configuration.

free of implant penetration in all specimens as well. For the PPMS configuration, the ulnar column was stabilized by a 3.5 mm fully threaded cortical screw. All procedures were carried out by a single senior elbow surgeon, following standard AO principles and in accordance with the manufacturer's instructions.

Mechanical testing

There were two types of mechanical testing methods carried out in our study: stiffness testing (static compression) and strength testing (load to failure/failure testing). All specimens were tested using a universal material testing machine (INSTRON ElectroPuls^{tm} E10000, Norwood, MA, USA) (Fig. 3). All specimens were firmly mounted to the corresponding fixture at the beginning of every mechanical tests. All the load modules were designed using 3D printing technique based on the contour of the composite bone.

For stiffness testing, posterior bending, axial compression and internal torsion were performed on thirty specimens (n=10 in each group) following the above sequence. According to the results of our pilot study and previous literature[21,22], load levels were chosen that allowed stiffness testing without plastic deformation of the implants or loosening between the specimen and the fixture. For stiffness testing under posterior bending (Fig. 4), each specimen was horizontally mounted to a custom-designed fixture with the dorsal side upward and clamped through a 3D-printed cylindrical sleeve (Polylactic acid, PLA) that fits the contour of the composite bone in the mid-shaft portion. Then, a maximum load of 50 N was applied in the direction perpendicular to the humeral shaft and the horizontal plane at a rate of 0.3 mm/min. For stiffness testing under axial compression (Fig. 5), each specimen was vertically placed on the fixture and the proximal humerus was rigidly held by four clamping bolts on each side. The distal fragment was closely fit using a metallic 3D-printed load module, whose upper surface was perpendicular to the longitudinal axis of the humeral shaft. Then, a maximum load of 200 N was applied along the longitudinal axis at a rate of 0.5mm/min. For stiffness testing under internal torsion (Fig. 5), the same fixture and clamping method employed in the axial loading tests were used, and a maximum torque of 10 N·m was applied to the distal fragment in a counterclockwise direction at a rate of 3°/min.

Fig. 3. Universal material testing machine (INSTRON ElectroPulstm E10000, Norwood, MA, USA).

For strength testing, another 18 specimens (n=6 in each group) were created following the above procedures and each specimen was loaded to failure under axial compression forces using the same fixture as above at a rate of 1 mm/min. Failure of the construct was defined as implant (plates or screws) breakage, fracture of the composite bone, cutoff or pull-out of screws, observable loosening of the bone-implant interface, or the distal fragment in contact with the proximal part of the composite humeri (5 mm gap closed).

Data analysis

OriginPro 2019b (OriginLab Corporation, Northampton, MA, USA) was used to evaluate the data. The stiffness of the construct was calculated by the slope of the load–displacement curve (posterior bending and axial compression tests) or the torque-degree curve (internal torsion tests) after linear fitting. The goodness of linear fitting (R^2) of each curve was also calculated. The strength of each construct was recorded as the ultimate load when the defined failure occurred. The type of failure in each specimen was recorded as well.

SPSS 24.0 (IBM Corp, Armonk, NY, USA) was used for statistical analysis. The quantitative data conforming to a normal distribution were recorded as the mean ± standard deviation ($\overline{\chi} \pm s$), and comparisons between groups were illustrated by histograms. If the homogeneity of variance was confirmed, one-way analysis of variance (ANOVA) was used to determine the difference between groups; if homogeneity of variance was not established, Welch ANOVA was used for the comparison and the significance level was adjusted by the Games-Howell method. The quantitative data without a normal distribution were recorded as the median (25th percentile, 75th percentile) [M (P25, P75)]. The comparison between groups was illustrated by box plots and analyzed using the Kruskal-Wallis H test. The Bonferroni method was used for post hoc comparison. Categorical data were recorded as numbers (percentages) and compared using the Pearson chi-square test, continuity correction or Fisher's exact test. A P value less than 0.05 was considered significant.

Results

For stiffness testing under posterior bending, the difference in mean stiffness values among the three fixation configurations was statistically significant (P<0.001) (minimal linear R^2>0.983). After post hoc comparison, the stiffness under posterior bending for the parallel configuration (131.81±9.55 N/mm) was significantly higher than that of the orthogonal configuration (85.70±7.30 N/mm) (adjusted P<0.001), and the orthogonal configuration was significantly stiffer than that of the PPMS configuration (53.85±11.10 N/mm) (adjusted P<0.001) (Fig. 6).

Under axial loading, the difference in mean stiffness values among the three groups was also statistically significant (P<0.001) (minimal linear R^2>0.988). Post hoc comparison showed that the

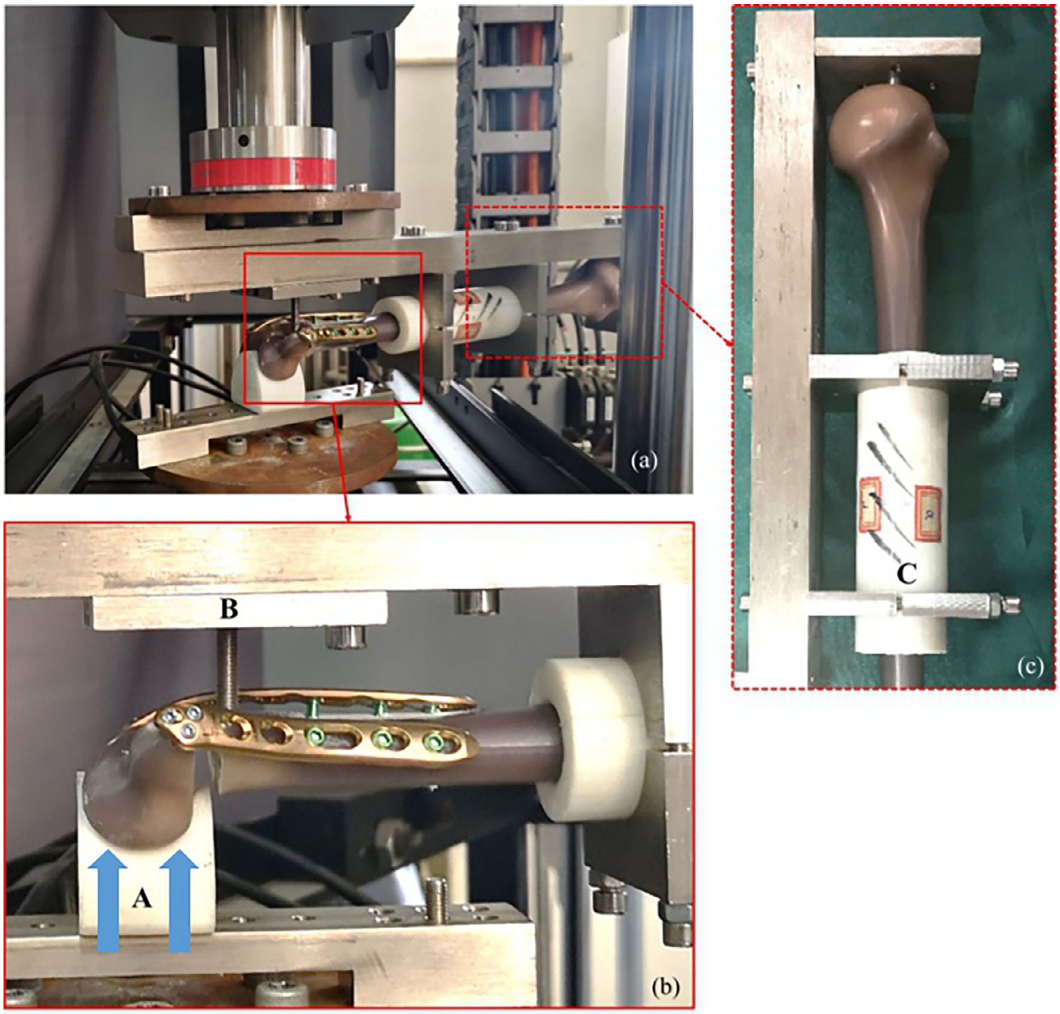

Fig. 4. (a) Posterior bending: the specimen was horizontally mounted to a custom-designed fixture (B) and clamped through a 3D-printed cylindrical sleeve (C) (Polylactic acid, PLA). A maximum load of 50 N was applied through a 3D-printed module (A) at a rate of 0.3 mm/min. (b) and (c): Partial enlarged view; the blue arrow is the direction of loading.

stiffness under axial compression for the parallel configuration [286.41 (278.92, 306.82) N/mm] was significantly higher than that of the orthogonal configuration [221.80 (199.66, 227.15) N/mm] (adjusted P=0.001) and PPMS configuration [212.38 (190.54, 225.16) N/mm] (adjusted P<0.001), respectively. However, a statistical difference was not detected between the orthogonal and PPMS configurations (adjusted P=1.000) (Fig. 6).

Under internal rotation, significant difference was revealed between the three types of implant configuration for the mean stiffness values (P<0.001) (minimal linear R^2>0.996). After post hoc comparison, we found that the stiffness under internal rotation for the parallel configuration [1.65 (1.60, 1.73) N·m/Deg] was significantly higher than that of the orthogonal configuration [1.44 (1.42, 1.51) N·m/Deg] (adjusted P=0.044), and the orthogonal configuration was significantly stiffer than that of the PPMS configuration [0.86 (0.79, 0.92) N·m/Deg] (adjusted P=0.029) (Fig. 6).

For the failure test under axial loading, there was a statistically significant difference in the mean load to failure among the three groups (P<0.001). After post hoc comparison, we found that the load to failure in the orthogonal group [839.44 (650.64, 922.62) N] was significantly lower than that of in the parallel group [1400.02 (1221.49, 1467.00) N] (adjusted P=0.009) and PPMS group [1360.99 (1346.57, 1399.37) N] (adjusted P=0.021), respectively. However, the difference between the parallel group and the PPMS group was not statistically significant (adjusted P=1.000) (Fig. 6).

Then, the types of construct failure were evaluated. All specimens had plastic deformation. Fourteen out of 18 specimens failed with screws cutting out as well as having a steep decline in the load–displacement curves. Four out of 18 specimens failed with distal fragments in contact with the proximal part of the composite humeri ("contact failure"). No specimen had breakage of the plates or screws. After further evaluating the types of screw cut-outs, three types were included (Fig. 7). First, "distal medial failure", which means fractures and screws cut out in the area covered by the distal portion of the medial plate. The second is "distal medial and trochlear failure", which means "distal medial failure" combined with fractures in the trochlear area. The third is "capitellar failure", which means capitellar fractures and screw cut-out in the distal part of the posterolateral plates.

In our study, all specimens in the orthogonal group demonstrated "distal medial failure", 2 specimens had "distal medial failure" and 4 specimens had "distal medial and trochlear failure" in the parallel group, and 4 specimens exhibited "contact failure" and 2 specimens had "capitellar failure" in the PPMS group.

Discussion

Usually, parallel and orthogonal double-plate configurations are the mainstream of surgical treatment options for distal humerus fractures. In our current study, the parallel configuration

Fig. 5. Axial compression loading and internal torsion: the specimen was vertically placed on the fixture and the proximal humerus was rigidly held by four clamping bolts on each side. The distal fragment was closely fit using a metallic 3D-printed load module. For axial loading, a maximum load of 200 N was applied along the longitudinal axis (blue arrow) at a rate of 0.5 mm/min. For internal torsion, a maximum torque of 10 N·m was applied in a counterclockwise direction (red arrow) at a rate of 3°/min.

demonstrated higher stiffness under axial compression, posterior bending and internal rotation as well as a higher ultimate load in axial loading to failure compared to the orthogonal configuration.

To the best of our knowledge, there have been no previous studies investigating parallel or orthogonal configurations using low transcondylar fracture models; however, the studies listed below adopted the same transverse fracture plane as in our research and their conclusions may still have reference value to our study. Of note, Varady et al. [20] reported significantly higher stiffness and resistance to failure in the parallel configuration under axial loading compared to the orthogonal double-plate for an AO type C2.3 fracture model, whose transverse osteotomy level was identical to that in our study. In addition, the use of the polyaxial anatomical plating system was found to provide better stability than monoaxial system for parallel construct, which may explain the superiority of the parallel configuration in our biomechanical tests. Using the same fracture models, Kudo et al. [23] also found significantly higher stiffness in the parallel configuration compared to the orthogonal construct when solely applying axial loading to the radial column of the distal humerus. However, no significant difference was detected during ulnar column axial loading, indicating that the parallel construct mainly provides additional support and protection to the lateral column of the distal humerus. Penzkofer et al. [19] created the same fracture models using 4th generation composite bone and demonstrated that the stiffness and median fatigue limit in the parallel double-plate configuration were significantly better than those of the orthogonal constructs under axial loading in 5-degree extension. Overall, the above results were basically consistent with our findings.

A meta analysis conducted by Shih et al. [24] in 2018 included 17 articles comparing biomechanical properties between parallel and orthogonal double-plate constructs, and found that the stiffness of the parallel configuration under axial and torsional loading was significantly superior to that of the orthogonal configuration, especially for supracondylar fractures. However, no differences were found under posterior/anterior bending (sagittal stiffness), which is inconsistent with our research. This outcome was likely due to the relatively higher level of the transverse osteotomy plane compared to our study when creating fracture models in some previous experiments. Thus, the volume of the distal fragment is usually large enough to allow sufficient screws for both parallel and orthogonal configurations. However, this is often not the case for low transcondylar fractures. This may explain why the stiffness of the parallel configuration under posterior bending was more superior in our study.

Further evaluating the type of construct failure, “medial distal failure” occurred in all specimens for the orthogonal group, which reflected the concentration of stress in this area. However, “medial distal and trochlear failure” was more likely to happen when parallel constructs were used in our experiment, and the load to failure was much higher than orthogonal constructs. We believe that for the parallel configuration, the arch-like structure [25] formed by the interlocking of several long transverse screws within the trochlear area can effectively disperse the localized stress in the distal portion of the medial plate and screws. In addition, this configuration increases the overall construct strength, especially for fractures with relatively small distal fragments. In this way, for the parallel configuration, when much higher forces (compared to those noted in the orthogonal construct) finally break the “arch”, the trochlear portion are the first to be affected, and the distal portion of the medial plate and screws fail subsequently due to the loss of stress protection by the “arch”. This may explain the superiority of the parallel double-plate construct to some extent.

However, low transcondylar fractures of the distal humerus are relatively simple in morphology but more prone to developing healing-related complications [5]. Therefore, some minimally invasive surgical strategies have been explored. Reising et al. [26] introduced a novel technique using a distal radial nailing system in the lateral column and a 1.8 mm K-wire in the medial side. However, the lack of a control group made the findings less valuable for clinical reference. Doğramaci et al. [27] introduced the double tension band technique using crossed K-wires from each side to the opposite column of the distal humerus, and tension wires were applied to tauten both medial and lateral column compression. However, the author reported significantly poorer stability of this construct than orthogonal double-plate osteosynthesis. Shimamura et al. [18] tested the biomechanical properties of a posterolateral ONI plate plus medial screw, a novel implant for low transcondylar fractures, and found it comparable to orthogonal double plating. In addition, Imatani et al. [6] proposed the application of a customized AO small T plate in the lateral column combined with a medial lag screw and reported good functional recovery without nonunion or delayed union. To some extent, the current trend favors the combination of lateral plates together with medial screws.

Our study used posterolateral LCPs in the lateral column with fully threaded cortical screws in the medial column (PPMS configuration). Despite the relatively lower stiffness of this construct compared to orthogonal and parallel double-plate configurations under posterior bending and internal torsion, the PPMS configuration was found to have comparable stiffness with the orthogonal configuration under axial loading; moreover, it had a similar ultimate load

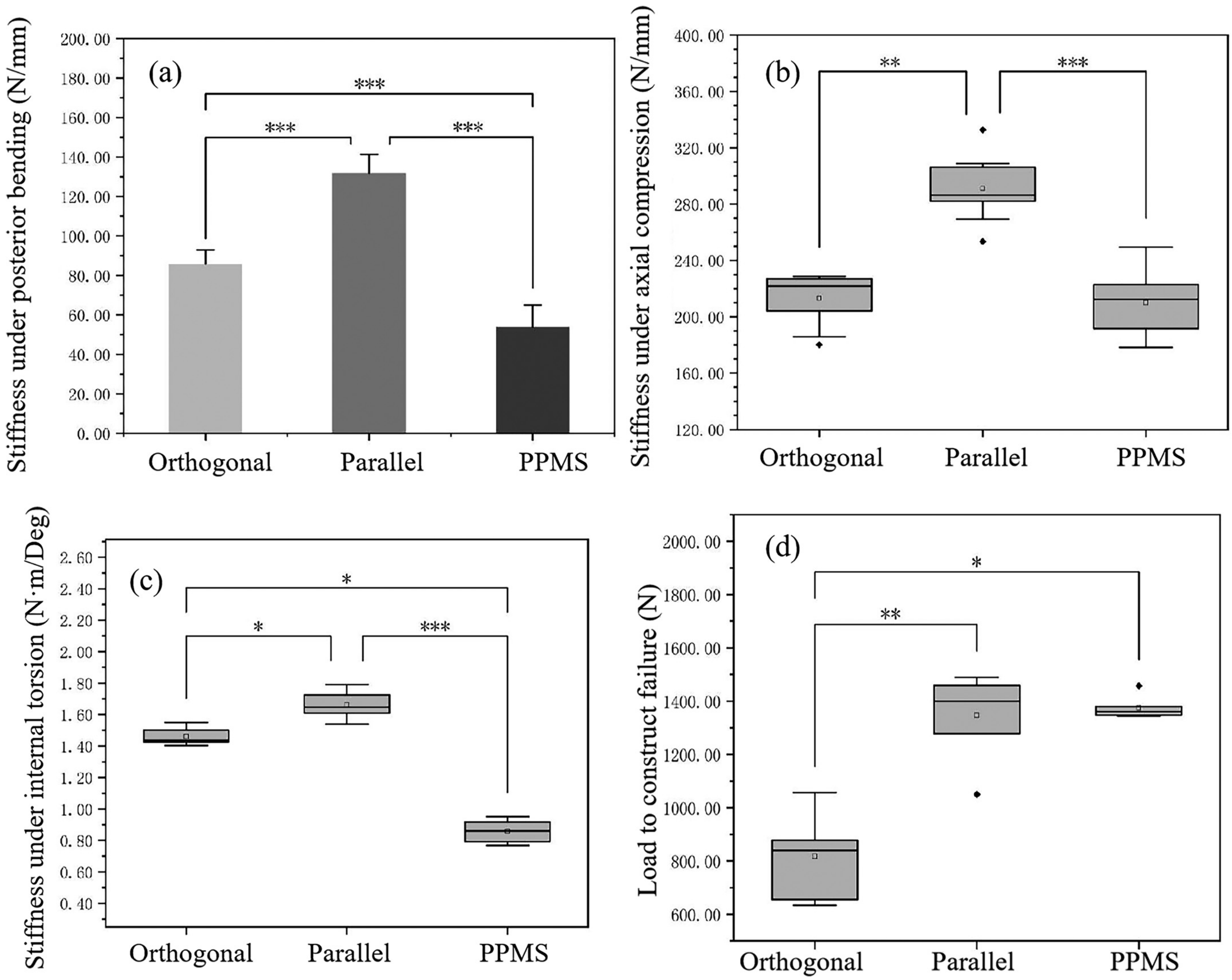

Fig. 6. Comparison of construct stiffness and load to failure among three configurations. (a) Posterior bending test. (b) Axial compression loading test. (c) Internal torsion test. (d) Ultimate load to construct failure under axial compression loading. Statistical difference denoted by * for P<0.05, ** for P<0.01 and *** for P<0.001.

in axial loading to failure relative to the parallel construct. In addition, most specimens in the PPMS group (4/6, 67%) failed when the distal fragment was in contact with the proximal part rather than loosening or breakage of plates and screws, indicating the relative advantages of the overall strength of the construct under axial failure loading. However, as far as we know, there is limited previous literature addressing its biomechanical properties.

Shimamura et al. [18] compared the strength of orthogonal and PPMS configurations for low transcondylar fracture models using cadaveric humeri. Under posterior bending, although without a significant difference, the orthogonal construct exhibited a higher failure load than the PPMS configuration (51.0±14.8 N vs 19.3±6.0 N). Nevertheless, under axial loading, the PPMS configuration was significantly weaker as well, which was inconsistent with our experiment. This outcome was likely due to the application of conventional reconstruction plates, which have a limited number of distal screws and less strength than locking compression plates. In addition, this outcome was likely influenced by the use of half-threaded cannulated screws in the medial column, which mainly provide sliding compressive forces at the fracture site instead of rigidly supporting the whole construct compared to fully threaded cortical screws. Therefore, the author might have underestimated the biomechanical properties of the PPMS construct. In another experiment conducted by Hungerer et al. [28], although not statistically significant, the researchers detected increased construct stiffness and median failure load under axial loading after inserting an additional interfragmentary long gap bridging screw, which is similar to the medial screw in our PPMS construct, through the most distal hole of the medial locking compression plate on the stabilization of parallel double-plate configuration. This observation indirectly demonstrated the effectiveness and feasibility of the medial column screw of the PPMS construct to some extent.

Our research provides a feasible surgical technique, the PPMS configuration, for low transcondylar fractures of the distal humerus. This construct is not only able to ensure relatively good mechanical stability but is also minimally invasive. Hence, it prevents the medial column periosteum from being extensively stripped and possibly reduces the risk of postoperative nonunion or delayed union to some extent. In addition, this configuration may alleviate irritation to surrounding soft tissue on the medial side due to implant and is cheaper than the double-plate configurations. Hence, this configuration may have certain clinical application value for low transcondylar fractures. It is worth noting that the medial fully threaded column screw can provide adequate stability especially for patients with sufficient bone stock in the medial epicondylar region.

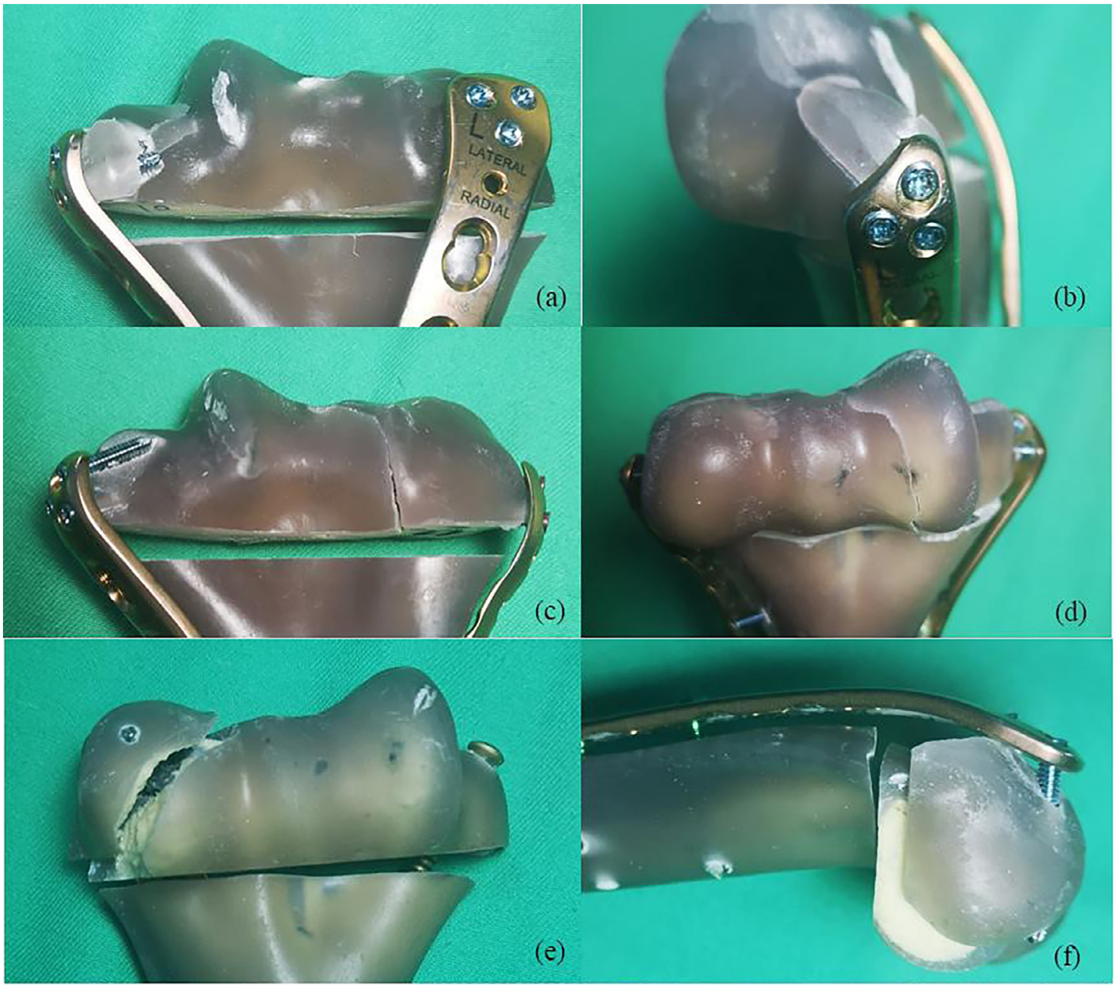

Fig. 7. Examples of construct failure when screw cutting-out and fractures occur. Three types are included: (a) (b) "distal medial failure"; (c) (d) "distal medial and trochlear failure"; (e) (f) "capitellar failure".

As with any study, there are certain limitations. First, artificial bones were used instead of cadaveric humeri, so we cannot closely simulate the biomechanical properties of live bones and soft tissue constraints by surrounding tendons and ligaments. However, the application of artificial bones ensures the uniformity of each specimen and thus focuses on the implant systems themselves and their mechanical performance. Second, three different loading protocols were successively performed on each specimen for stiffness testing, which may adversely affect the accuracy of the testing results. However, all specimens were tested in the same exact order without any plastic deformation thus reducing experimental errors to the greatest extent possible. Third, our current study did not involve stiffness or failure tests under cyclic loading, which can be used to further evaluate and compare the biomechanical properties of different configurations against structural fatigue. Finally, it is still unknown whether the differences found in stiffness and strength among the three configurations have clinical relevance, especially for the PPMS construct. Therefore, further clinical trials are required to validate the clinical outcomes of these configurations.

Conclusion

In the treatment of low transcondylar fractures of the distal humerus, the overall stiffness and strength of the parallel configuration were superior to those of orthogonal double plates as well as PPMS configurations with regard to the stiffness under posterior bending, axial loading, internal torsion and the load to failure under axial compression forces. Nevertheless, the PPMS configuration can provide adequate stability and stiffness comparable to the orthogonal configuration and the strength to resist construct failure equivalent to the parallel configuration under axial compression loading. With the advantages of being minimally invasive, causing fewer irritation problems, and being less expensive, the PPMS construct may have certain clinical value for the treatment of transcondylar fractures.

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Declaration of Competing Interest

All authors of this study, their immediate family, and any research foundation with which they are affiliated did not receive any financial payments or other benefits from any commercial entity related to the subject of this article.

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References

[1] Nauth A, McKee MD, Ristevski B, Hall J, Schemitsch EH. Distal humeral fractures in adults. J Bone Joint Surg Am 2011;93(7):686–700.
[2] Amir S, Jannis S, Daniel R. Distal humerus fractures: a review of current therapy concepts. Curr Rev Musculoskelet Med 2016;9(2):199–206.
[3] Robinson CM, Hill RM, Jacobs N, Dall G. Court-Brown CM. Adult distal humeral metaphyseal fractures: epidemiology and results of treatment. J Orthop Trauma 2003;17(1):38–47.
[4] Park JS, Kim YT, Choi SJ. Crisscross-type screw fixation for transcondylar fractures of distal humerus in elderly patients. Arch Orthop Trauma Surg 2015;135(1):1–7.
[5] Simone JP, Streubel PN, Sanchez-Sotelo J, Morrey BF. Low transcondylar fractures of the distal humerus: results of open reduction and internal fixation. J Shoulder Elbow Surg 2014;23(4):573–8.
[6] Imatani J, Ogura T, Morito Y, Hashizume H, Inoue H. Custom AO small T plate for transcondylar fractures of the distal humerus in the elderly. J Shoulder Elbow Surg 2005;14(6):611–15.
[7] Leigey DF, Farrell DJ, Siska PA, Tarkin IS. Bicolumnar 90-90 plating of low-energy distal humeral fractures in the elderly patient. Geriatr Orthop Surg Rehabil 2014;5(3):122–6.
[8] Paryavi E, O'Toole RV, Frisch HM, Andersen RC, Eglseder WA. Use of 2 column screws to treat transcondylar distal humeral fractures in geriatric patients. Tech Hand Up Extrem Surg 2010;14(4):209–13.
[9] Abzug JM, Dantuluri PK. Use of orthogonal or parallel plating techniques to treat distal humerus fractures. Hand Clin 2010;26(3):411–21 vii.
[10] Lauder A, Richard MJ. Management of distal humerus fractures. Eur J Orthop Surg Traumatol 2020;30(5):745–62.
[11] Mighell MA, Stephens B, Stone GP, Cottrell BJ. Distal humerus fractures: open reduction internal fixation. Hand Clin 2015;31(4):591–604.
[12] Frechette GM, Chan JJ, Kim JM, Xiao RC, Hausman MR. The outcomes of intra-articular distal humerus open reduction internal fixation using parallel precontoured plates in the elderly. J Hand Surg Am 2022 Apr 7 S0363-5023(22)00096-X.
[13] Kaiser T, Brunner A, Hohendorff B, Ulmar B, Babst R. Treatment of supra- and intra-articular fractures of the distal humerus with the LCP Distal Humerus Plate: a 2-year follow-up. J Shoulder Elbow Surg 2011;20(2):206–12.
[14] Arnander MW, Reeves A, MacLeod IA, Pinto TM, Khaleel A. A biomechanical comparison of plate configuration in distal humerus fractures. J Orthop Trauma 2008;22(5):332–6.
[15] Koonce RC, Baldini TH, Morgan SJ. Are conventional reconstruction plates equivalent to precontoured locking plates for distal humerus fracture fixation? A biomechanics cadaver study. Clin Biomech (Bristol, Avon) 2012;27(7):697–701.
[16] Caravaggi P, Laratta JL, Yoon RS, et al. Internal fixation of the distal humerus: a comprehensive biomechanical study evaluating current fixation techniques. J Orthop Trauma 2014;28(4):222–6.
[17] Taylor PA, Owen JR, Benfield CP, Wayne JS, Boardman ND 3rd. Parallel plating of simulated distal humerus fractures demonstrates increased stiffness relative to orthogonal plating with a distal humerus locking plate system. J Orthop Trauma 2016;30(4):e118–22.
[18] Shimamura Y, Nishida K, Imatani J, et al. Biomechanical evaluation of the fixation methods for transcondylar fracture of the humerus:ONI plate versus conventional plates and screws. Acta Med Okayama 2010;64(2):115–20.
[19] Penzkofer R, Hungerer S, Wipf F, von Oldenburg G, Augat P. Anatomical plate configuration affects mechanical performance in distal humerus fractures. Clin Biomech (Bristol, Avon) 2010;25(10):972–8.
[20] Varady PA, von Rüden C, Greinwald M, Hungerer S, Pätzold R, Augat P. Biomechanical comparison of anatomical plating systems for comminuted distal humeral fractures. Int Orthop 2017;41(9):1709–14.
[21] Atalar AC, Tunalı O, Erşen A, Kapıcıoğlu M, Sağlam Y, Demirhan MS. Biomechanical comparison of orthogonal versus parallel double plating systems in intraarticular distal humerus fractures. Acta Orthop Traumatol Turc 2017;51(1):23–8.
[22] Stoffel K, Cunneen S, Morgan R, Nicholls R, Stachowiak G. Comparative stability of perpendicular versus parallel double-locking plating systems in osteoporotic comminuted distal humerus fractures. J Orthop Res 2008;26(6):778–84.
[23] Kudo T, Hara A, Iwase H, et al. Biomechanical properties of orthogonal plate configuration versus parallel plate configuration using the same locking plate system for intra-articular distal humeral fractures under radial or ulnar column axial load. Injury 2016;47(10):2071–6.
[24] Shih CA, Su WR, Lin WC, Tai TW. Parallel versus orthogonal plate osteosynthesis of adult distal humerus fractures: a meta-analysis of biomechanical studies. Int Orthop 2019;43(2):449–60.
[25] O'Driscoll SW. Optimizing stability in distal humeral fracture fixation. J Shoulder Elbow Surg 2005;14(1):186S–194S Suppl S.
[26] Reising K, Konstantinidis L, Helwig P, Wagner FC, Südkamp NP, Strohm PC. Biomechanical testing of an innovative fixation procedure to stabilize olecranon osteotomy. Proc Inst Mech Eng H 2014;228(11):1146–53.
[27] Doğramaci Y, Esen E, Kürklü M, Kirici Y, Atahan AO, Kömürcü M. Double plate osteosynthesis provides better biomechanical stabilization than double tension band technique in distal humerus fractures. Eklem Hastalik Cerrahisi 2010;21(1):44–9.
[28] Hungerer S, Wipf F, von Oldenburg G, Augat P, Penzkofer R. Complex distal humerus fractures-comparison of polyaxial locking and nonlocking screw configurations-a preliminary biomechanical study. J Orthop Trauma 2014;28(3):130–6.